The microstructure and technological properties of ultra high strenght 1100 mpa grade strip steel

P. Suikkanen, M. Hemmilä, J. Erkkilä, E. Virolainen, S. Tihinen, T. Saarinen, T. Liimatainen, V. Kesti, J. Kömi

The article describes the microstructure and the technological properties of a direct quenched ultra-high strength strip steel with the minimum specific yield strength of 1100MPa. The microstructure of this low carbon, Mn-Cr-Mo-Cu-Ni alloyed steel consists mainly of auto-tempered lath martensite. Due to the sophisticated thermo-mechanical controlled processing schedule, the martensite transformation takes place from a fine and uniform austenite grain structure. State-of-the-art steelmaking and continuous casting operations guarantee a good inclusion cleanness and low level of segregation. The steel has excellent impact and fracture toughness properties with respect to its ultra-high strength level. The determined transition temperature for 28J in Charpy-V test and fracture toughness characteristic temperature, T_0, were below -100°C. The weldability tests indicated that the impact toughness of the heat affected zone (HAZ) is excellent and there is no significant softening in the HAZ or in the welded joint in the wide range of $t_{8/5}$ cooling times. The steel allows crack-free bending with a minimum inside bending radius equal to 3 times material thickness irrespective of the bending direction. In addition, the steel has a good resistance to atmospheric corrosion.

Keywords: Martensite - Direct quenching - Strength - Impact toughness - Fracture toughness - Weldability - Bendability - Corrosion resistance.

INTRODUCTION

Ultra-high strength steels with the minimum specific yield strengths of 960 and 1100 MPa with the proprietary names Optim 960 QC, Optim 1100 QC and are made using hot strip rolling and direct quenching followed by leveling and cutting to plates with thicknesses in the range 2.5 – 8.0 mm [1,2]. Due to thermomechanical rolling combined with direct quenching and low carbon content, a good combination of strength, toughness and formability is achieved without tempering [2,3].The steels are typically used in light-weight mobile structures like containers as well as booms, arms and other structural members of mobile lifting equipment. One of the typical features of 1100MPa grade QC steels, as well as 1100MPa grade quenched and tempered steels, is that they tend to soften during high heat input welding. The softening does not limit their use in some demanding structural applications. However, the softening must be taken into account in structural design and joint type [4]

One of the steel producer's main challenges is to manufacture an ultra-high strength structural steel with an extremely good combination of toughness, formability and weldability. The purpose of this article is to summarize test results from a pilot scale trials to produce an ultra-high strength steel with high performance.

Pasi Suikkanen, Mikko Hemmilä, Juha Erkkilä, Esa Virolainen, Sakari Tihinen, Tuomo Saarinen, Tommi Liimatainen, Vili Kesti, Jukka Kömi

Ruukki Metals Oy, Finland

Paper presented at the Int. Conf. ROLLING 2013, Venice 10-12 June 2013, organized by AIM

COMPOSITION, PROCESSING AND MICROSTRUCTURE

Information regarding the chemical composition of the investigated 1100MPa grade strip steel is given in Table 1. The alloying philosophy relies on the low carbon content of about 0.09 wt-%. The desired transformation structure is achieved by controlling the content of the elements of Mn, Cr, Cu and Ni, so that the steel has the cracking parameter (Pcm) value of 0.29. It should be also emphasized that V, Nb, Ti or B micro-alloying is not applied and their contents

	Si	Mn	P	S	Cr	V	Nb	B	Others	Pcm
0.09	0.2	1.1	>0.007	>0.0010	1.2	residual			Mo, Cu, Ni,	0.29

Tab. 1 - Chemical composition of the investigated 1100MPa grade strip steel in wt-%.

Tab. 1 - Composizione in peso% dei nastri di acciaio di grado 1100MPa esaminati

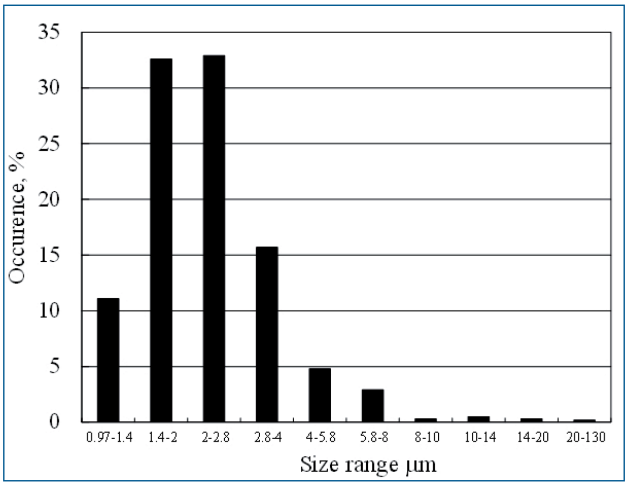

Fig. 1 - Inclusion size distribution for the investigated steel 1100MPa grade strip steel.

Fig. 1 – Distribuzione delle dimensioni delle inclusioni per nastri di acciaio di grado 1100MPa.

were at the residual levels. Due to the state-of-the-art steelmaking impurity levels for S, P and N are low.

The steelmaking operations included basic oxygen steelmaking combined with ladle furnace and vacuum degassing processing. The steel was continuously cast with special attention paid on the cast temperature, secondary cooling strategy and dynamic soft-reduction parameters. Aforementioned measures are prerequisites for the low impurity levels and reduction of non-metallic inclusion as well as low level of segregation. The typical inclusion size distribution of the investigated steel, as determined by SEM-EDS technique, is shown in Figure 1. The non-metallic inclusions were mostly finer than 10 µm and they were typically spherical calcium aluminates.

The steel was thermo-mechanically controlled processed from 210 mm thick slab to a final thickness of 6 mm and direct quenched to room temperature. Typical transformation microstructure is shown Figure 2 a. The transformation microstructure consists mainly of martensite. Martensite in these steels is partially auto-tempered due to the low carbon content and relatively high martensite start temperature. Carefully designed hot rolling schedule guarantees that the transformation to martensite takes place from fine and uniform prior austenite structure. The mean grain size, as determined by the mean linear intercept method in the normal direction, is ~10 µm, Figure 2 b.

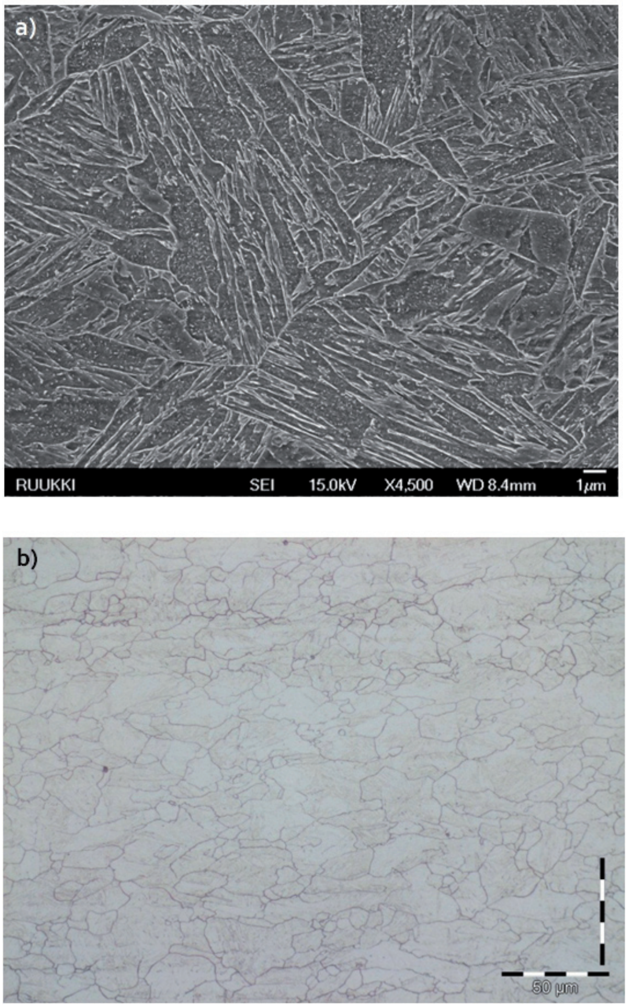

Fig. 2 - Auto-tempered martensitic transformation (a) and the prior austenite structure (b).

Fig. 2 - Martensite auto-temprata (a) e precedente struttura austenitica (b).

TENSILE PROPERTIES

Tensile tests were performed at room temperature in accordance with the European standard EN 10002 using flat specimens (6 x 20 x 120 mm^3), cut both in longitudinal and transverse directions relative to the rolling direction. The main results are summarized in Table 2. The steel fulfils the minimum yield strength of 1100MPa in both transverse and longitudinal direction. The tensile strength is above 1250MPa. This leads to yield-to-tensile strength-ratio of ~0.90. The total elongation at fracture and uniform elongation values are ~11 % and ~2%, respectively.

IMPACT TOUGHNESS

Charpy -V impact tests were carried out at various temperatures (3 specimens/temperature) ranging from 20°C to -150°C using sub-size specimens of 5 x 10 x 55 mm^3 taken both in the longitudinal and transverse directions relative to the rolling direction. Charpy-V transition curves tested in longitudinal and transverse directions are exhibited in Figures 3 a and b, respectively.

As can be seen from the figures, the steel has excellent impact toughness properties taking into account the ultra-high strength level. The upper shelf energies of the sub-size specimens were in the range of 38-55J. In the case of full size Charpy-V specimens (10x10x55 mm3), the aforementioned values correspond with 95-138 J/cm^2. The macroscopic fracture mode remained ductile even down to -60 °C. The transition temperatures for 14J (T14J) for the sub-size specimens in longitudinal and transverse directions were -146 °C and -138 °C, respectively. The transition temperature of 14J in the 5 mm thick specimen equivalents with 34J/cm^2 in a full-size specimen. From the T14J value, one can determine the transition temperature for 28J in full size specimens according to the procedure described in Ref [5]. The determined T28J values were -125°C for the longitudinal specimens and -116°C for transverse specimens.

FRACTURE TOUGHNESS

In order to determine the resistance against brittle fracture, the fracture toughness tests were carried out according to standard ASTM E 1921. From the test results, so called fracture toughness reference temperature, T_0, was determined. The T0 temperature is determined as a temperature at which the median fracture toughness (K_{Jc}) of 1T size specimens equals 100 MPa $\sqrt{m}$. Fracture toughness as a function of temperature is shown in Figure 4 a and b for longitudinally and transverse tested samples. Also, so called Master Curve fittings [6] with 5, 50 and 95 % fracture probabilities are included in both figures. It is seen from the Figures 4 a and b that the steel behaves in a ductile manner even down to temperatures -100°C. The results indicate, in conjunction with the impact toughness test results, the safe applicability of the steel to low temperature service.

WELDABILITY

Evaluation of weldability was carried out using a MAG welding process. The calculated t8/5-cooling time during the welding was 7 seconds in run 1 (E=0.6 kJ/mm) and 15 seconds in run 2 (E=0.9 kJ/mm). The used filler material was Union X 96 with the minimum yield strength of 890MPa. The used joint type was a butt joint with 50° Y-groove and a 0.5 mm root face.

The hardness profiles over the weld are shown in Figure 5.

	Rp0.2	Rm	Elongation at fracture	Uniform elongation	Rp0.2/ Rm
	MPa	MPa	%	%	-
Longitudinal	1149	1272	11.8	2.3	0.90
Transverse	1140	1295	11.0	2.2	0.88

Tab. 2 - Summary of tensile properties of 1100 MPa grade strip steel.

Tab. 2 – Caratteristiche di resistenza a trazione dei nastri di acciaio di grado 1100MPa

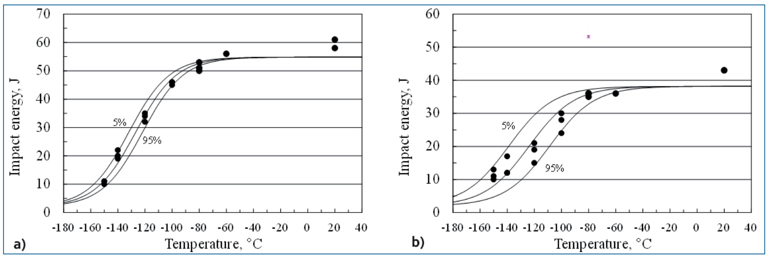

Fig. 3 - Charpy-V transition curves for specimens tested in transverse direction (T14 J= -146°C), (a) and for specimens tested in longitudinal relative to RD (T14J = -138°C) (b).

Fig. 3 – Curve di transizione Charpy-V per campioni sottoposti a prove in direzione trasversale (T14 J= -146°C), (a) e per campioni sottoposti a prove in direzione longitudinale rispetto a quella di laminazione (T14J = -138°C) (b).

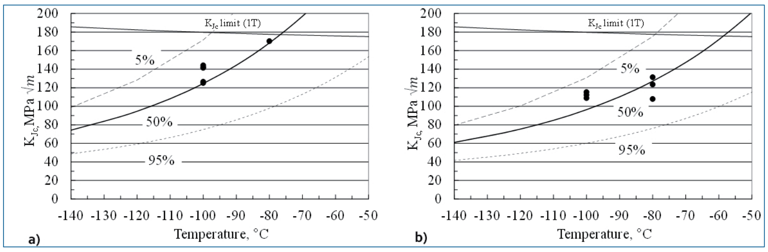

Fig. 4 - Fracture toughness for longitudinally tested (T_0 = -116 °C) specimens (a) and transverse tested (T_0 = -96 °C) specimens (b).

Fig. 4 – Resistenza alla frattura per (a) campioni longitudinali (T_0 = -116 °C) e (b) campioni trasversali (T_0 = -96 °C).

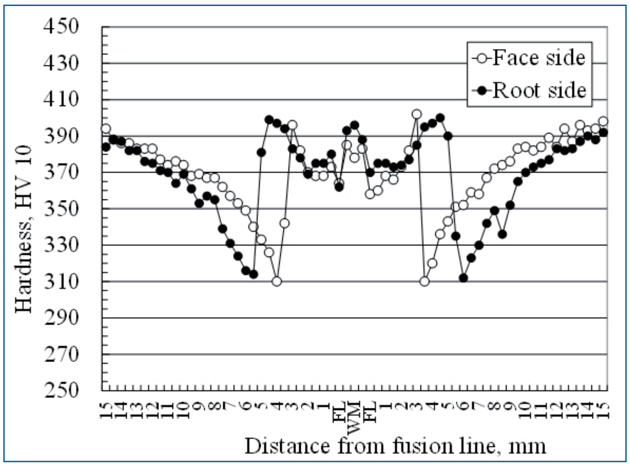

Fig. 5 - The hardness profiles over the weld as measured 1,5 mm from root and face side of the weld.

Fig. 5 – Profili di durezza sulla saldatura misurati a 1,5 mm dalla radice e dal fronte della saldatura.

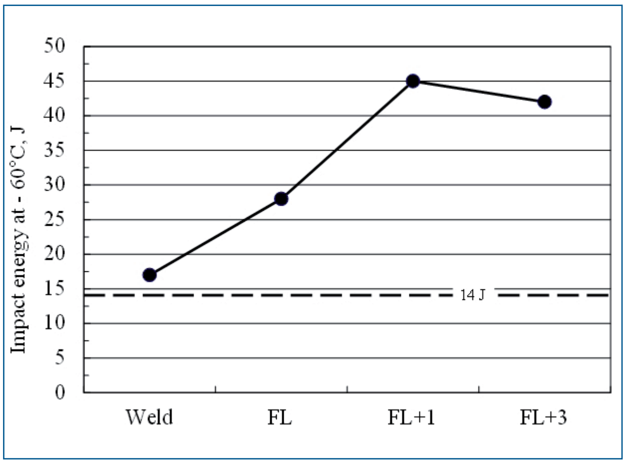

Fig. 6 - Impact toughness energies at -60 °C determine from the weld metal, fusion line (FL) and 1mm (FL+1) and 3 mm (FL+3mm) from the fusion line. The specimen thickness is 5 mm.

Fig. 6 - Resilienza a -60 °C determinata sul metallo saldato, sulla linea di fusione (FL), a 1 mm (FL+1) e a 3 mm (FL+3mm) dalla linea di fusione. Lo spessore del provino è 5 mm.

The heat cycle during welding causes a narrow softened zone. However, the softened zone is narrow and it does not decrease the strength of the weld significantly, Table 3. The yield strength of the welded joint exceeds the yield strength (890 MPa) of the weld metal. The tensile strength of the weld exceeds the designed yield strength of the parent material (1100 MPa). The place of the fracture of tensile test samples was always in the heat affected zone (HAZ). The joint passed the transverse bending tests according to standard EN 15614-1 when the mandrel size was 94 mm.
The Charpy-V impact toughness energies at -60 °C with

Rp0.2	Rm	A5	Fracture location
MPa	MPa	%	
1032	1137	4.1	HAZ
1031	1138	4.4	HAZ

Tab. 3 - Tensile properties of the weld joint.

Tab. 3 – Caratteristiche di resistenza a trazione del giunto saldato.

notches located at the weld metal, at fusion line, 1mm from fusion line (FL+1mm) and 3 mm from fusion (FL + 3mm) are presented in Figure 6. The impact toughness properties of the heat affected zones were good, fulfilling impact energy requirement of 14 J at -60 °C, (14J in 5 mm thick specimen corresponds 34J/cm^2 in a full size Charpy-V specimen). The lowest impact energies were found in the weld metal.
The welding tests assign that the investigated 1100MPa grade strip steel can be efficiently welded by all conventional welding processes; the impact toughness, strength and formability of the welded joint still remain at qualified level.

BENDABILITY

The formability of the steel was evaluated by three point bending tests. The bendability is generally measured as a ratio of the punch radius (R) to the strip thickness (t) that the steel can tolerate without any sign of surface cracks or "nut shape" of the bent as bent to the angle of 90º in the bending test [7]. Table 4 summarizes the results from bending tests. The steel exhibits good bendability properties relative to the strength level. The minimum bending radius is 3 times the strip thickness when the bending line is in the parallel relative to the rolling direction. In the transverse direction even a more extreme bending radius (2.3 t) is allowed. Figure 7 depicts shape and surface quality of the bent with the bending radius of 2.3 t.

Orientation	Strip thickness, t	Punch Radius, R	Minimum allowed bending radius
Longitudinal	6	18	3.0·t
Transverse	6	14	2.3·t

Tab. 4 - Summary of the bending test results.

Tab. 4 - Riepilogo dei risultati delle prove di piega.

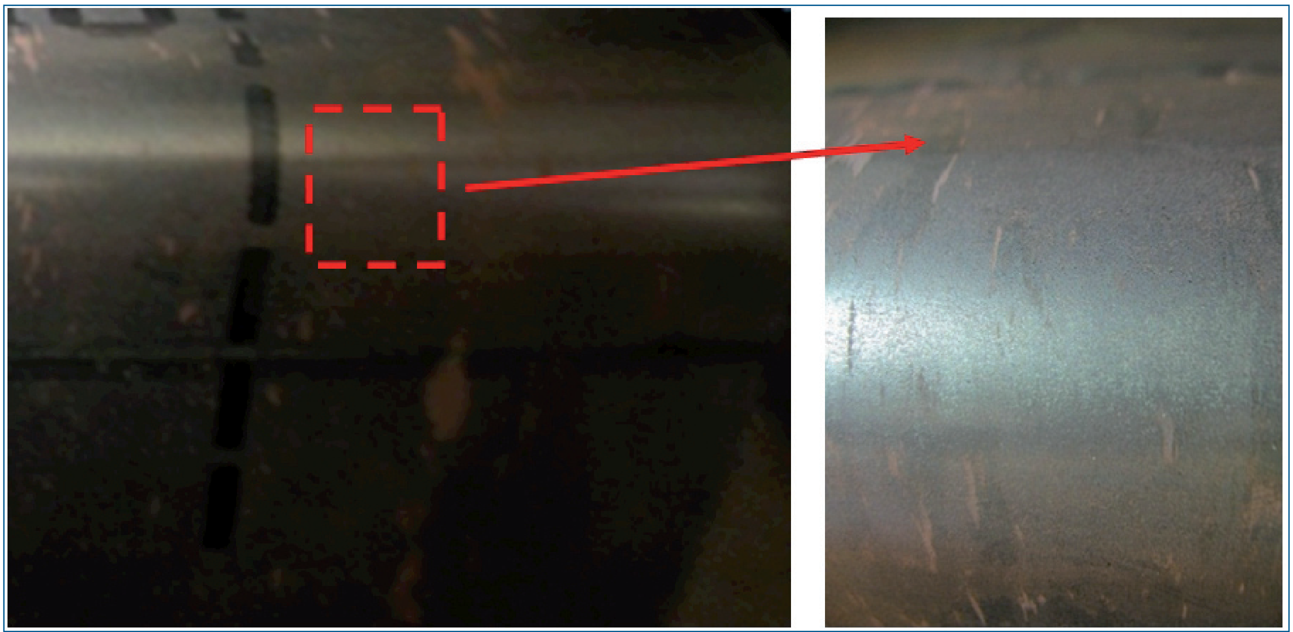

Fig. 7 - Shape and surface quality of bended 1100MPa grade strip steel, bending line in transverse direction relative to the rolling direction (R=2.3t).

Fig. 7 – Forma e qualità superficiale del nastro in acciaio di grado 1100 Mpa dopo prova di piega, linea di piega in direzione trasversale rispetto alla direzione di laminazione (R=2.3t).

CORROSION PROPERTIES

The resistance to atmospheric corrosion was evaluated by a salt spray test. The specimens were subjected to a neutral salt spray test (5% NaCl solution at 35°C) for 480 h. Corten A and 355 grade mild steels were chosen as reference materials. The results from the salt spray test are summarized in Figure 8 as a loss of weight per square meter (g/m^2) and an annual corrosion rate (µm/a). The test results suggest that the investigated steel has a good resistance to corrosion in salt spray test conditions. For example, the investigated 1100 MPa grade strip steel exhibits ~42 % and ~58% lower mass loss per unit area than Corten A and 355 mild steels, respectively.

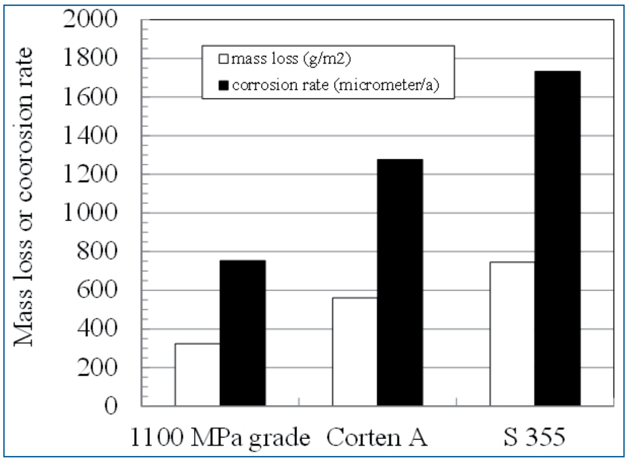

Fig. 8 - Loss of weight per square meter (g/m^2) and as an annual corrosion rate (µm/a) for the 1100MPa grade strip steel and Corten A and S 355 mild steel

Fig. 8 – Perdita in peso per metro quadrato (g/m^2) e velocità di corrosione annuale (µm/a) per il nastro in acciaio di grado 1100Mpa, per il Corten A e per l'acciaio dolce S 355.

DISCUSSION

The results have clearly demonstrated that 1100MPa grade strip steel can be produced by using low carbon steel (0.09 wt-%) with Pcm value of about 0.29. The recent results have also showed that Pcm value (i.e. alloy content) can be significantly lowered to about 0.24-0.26 while maintaining the good combination strength, toughness and weldability in 0.09 wt-% of carbon containing steels [8]. This significantly improves the cost-effectiveness of this steel concept.
The toughness properties are at a good level. The good toughness properties are assumed to derive from the auto-tempered lath martensite structure, fine and uniform austenite grain size and good inclusion cleanliness [9]. However, it should be noted that the relation between the T0 and the T28J temperatures does not follow the general 'Fitnet' based correlation; thus, estimating the fracture toughness from Charpy data would lead to severely unconservative KJc estimates. However, it should be noted that both the impact and the fracture toughness of the in-

vestigated steel are excellent and the steel can be applied in structural applications for low temperature service

The bendability properties appear to be equal to quenched and tempered steels. In direct quenched steels, the main factors controlling the bendability properties are the inclusion cleanliness [9], surface transformation texture, austenite grain morphology and the surface transformation microstructure [10]. The absence of elongated MnS inclusion, low intensity of ~{112}<111> transformation texture components, often associated with equi-axed austenite grain structure, and martensitic transformation structures near the strip surface are preconditions for good bending properties. In addition, although the elongation values in the tensile test were relative modest (Table 2), the bendability still remains at good level. Therefore, it appears that tensile test elongation values do not directly predict the bendability properties of direct quenched strip steels [10].

The weldability of 1100 MPa grade strip steel is superior with respect to the impact toughness of the fusion line and HAZ even with rather long t8/5 cooling time (15s). This is attributed to its low carbon, applied alloy contents and good inclusion cleanliness. The softening of the HAZ is limited only very narrow regions and the strength of the welded joint is not significantly weakened. The good resistance to softening has been found to derive from the applied Cr-Ni-Cu alloying [8]. The aforementioned alloying has been found to be particulate effective to prevent softening in the inter-critical parts of HAZ. It is proposed that Cu and Ni alloying contributes both refinement of effective grain size and precipitation hardening via Cu-precipitates [8,11].

The applied alloy content also improves weather resistance of the investigated 1100 MPa grade strip steel to atmospheric corrosion compared with other steels. Typically, the good weather resistance is attributed to steel chromium, nickel and copper alloying [12]. These elements form a protective layer on its surface under the influence of the weather. The corrosion-retarding effect of the protective layer is produced by the particular distribution and concentration of alloying elements in it. The layer protecting the surface develops and regenerates continuously when subjected to the influence of the weather. The good weather resistance reduces the need for repair painting of the structure. This improves the economy and life time of the structure made of this steel.

The results presented here have demonstrated that an outstanding combination of technological properties can be achieved in low carbon steel produced via thermo-mechanical rolling and direct quenching. The results have increased the understanding of the physical metallurgy and the structure–property relations of direct quenched steels. This enables the further development of the present QC strip grades.

SUMMARY

The present paper has demonstrated that a low carbon ultra-high strength strip steel with a supreme combination of strength, toughness, formability and weldability can be simply produced via direct quenching process. The results indicate that the steel can be applied even in the most demanding structural applications. The results also open new opportunities for further development of low carbon direct quenched strip steel family in the strength grade range of 960-1100MPa.

ACKNOWLEDGEMENTS

Funding of The Finnish Funding Agency for Technology and Innovation (Tekes) is gratefully acknowledged.

REFERENCES

1] M. HEMMILÄ, R. LAITINEN, T. LIIMATAINEN and D. PORTER, Proc. 1st Int. Conf. “Super-High Strength Steels”, Rome, Italy, AIMET (2005). CD-ROM

2] A.J. KAIJALAINEN, P.P. SUIKKANEN, L.P. KARJALAINEN, J.I. KÖMI, A.J. DEARDO, Proc. 2nd Int. Conf. Super-High Strength Steels, Peschiera del Garda, Italy, AIM, 2010. CD-ROM

3] A.J. KAIJALAINEN, P.P. SUIKKANEN, T.J. LIMNELL, L.P. KARJALAINEN J.I. KÖMI, D.A. PORTER, J. Alloys Compounds, (2012).

4] T. BJÖRK, J. TOIVONEN, T. NYKÄNEN, IIW Document XV-1356-10.

5] K. WALLIN, Fracture Toughness of Engineering Materials, EMAS Publishing, Birchwood Park UK (2011), p 279.

6] D.E. MCCABE, J.G. MERKLE & K. WALLIN, An Introduction to the Development and Use of the Master Curve Method. ASTM International, West Conshohocken (2005), p. 38.

7] J. HEIKKALA, A. VÄISÄNEN, Proc. 11th Biennial Conf. on Engineering Systems Design and Analysis, Nantes, France, 2012.

8] J. HANNULA, The effect of composition and processibility and weldability on S1100 strength class steel, Master thesis, University of Oulu, Oulu, Finland (2007), p. (in Finnish)

9] A. KAIJALAINEN, P. KARJALAINEN, D. PORTER, P. SUIKKANEN, J. KÖMI, V. KESTI, T. SAARINEN, Proc.8th Int. Conf. CLEAN STEEL, Budapest, Hungary (2012), p. 1.

10] A. KAIJALAINEN, Internal Report, University of Oulu, Oulu, Finland (2010), p 38.

11] X. YU, Characterization and Modeling of Heat Affected Zone Microstructure in a Blast Resistant Steel, Master Thesis, Ohio State University, Columbus, Ohio (2009), p 88.

12] M. VEIJOLA, Development of an ultra-high strength weathering steel, Master Thesis, University of Oulu, Oulu, Finland (2007), p. 18.

MICROSTRUTTURA E CARATTERISTICHE TECNOLOGICHE DI NASTRO IN ACCIAIO ULTRA ALTORESISTENZIALE DI GRADO 1100 MPA

Parole chiave: Acciaio - Martensite - Caratterizzazione materiali - Corrosione

Il presente articolo descrive la microstruttura e le proprietà tecnologiche di un nastro temprato direttamente, in acciaio ad ultra-alta resistenza, con limite di snervamento specifico minimo di 1100MPa. La microstruttura di questa lega di acciaio a basso carbonio con Mn-Cr-Mo-Cu-Ni, è costituita principalmente da martensite lamellare auto-temperata. Grazie al sofisticato programma di processo termomeccanico controllato, la trasformazione martensitica si origina da una struttura a grano austenitico fine ed uniforme. Le conoscenze sulle operazioni siderurgiche di colata continua garantiscono un buon grado di purezza inclusionale e un basso livello di segregazione. Questo acciaio ha mostrato eccellenti proprietà di resistenza all'impatto e alla meccanica della frattura tenuto conto della sua ultra-alta resistenza. La temperatura di transizione per 28J nella prova Charpy - V e la temperatura caratteristica per la tenacità alla frattura, T_0, sono posizionate al di sotto di -100C. Le prove di saldabilità hanno dimostrato un'eccellente valore di resilienza della zona termicamente alterata (ZTA) e non vi è stato alcuna significativa perdita di caratteristiche nella ZTA o nel cordone di saldatura, in un ampio intervallo di tempi di raffreddamento $t_{8/5}$. L'acciaio permette una piegatura senza formazione di cricche per un raggio interno minimo pari a 3 volte lo spessore del materiale, indipendentemente dalla direzione di piegatura. Inoltre, l'acciaio ha una buona resistenza alla corrosione atmosferica.